SIMULATION OF WATER SOIL EROSION EFFECTS ON SEDIMENT DELIVERY TO DOBCZYCE RESERVOIR

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ABSTRACT:

Synoptic information on suspended matter inflow into reservoirs is important because of the potential storage capacity reduction and water contamination. Such prognosis is difficult to obtain only from in situ measurement. This can be solved by modeling water soil erosion effect using Digital Elevation Model, climate data, soil type parameters and land-use/land-cover data obtained from remote sensing multitemporal imageries. To predict sediment yields from watersheds a calibrated model is needed. The paper presents a study related to the Dobczyce Reservoir, located in the southern part of Poland. In 1980s detailed measurements of sediment yields in its immediate watershed rivers were done. We tried to calibrate an erosion model to predict sediment loads. From many existing soil erosion modeling approaches which could be used as a tool for sediment delivery estimations, the RUSLE approach together with sediment delivery ratio estimation was chosen. The results obtained show the existing potential of this simple approach to predict the sediment delivery to Dobczyce Reservoir from its immediate watershed.

1. INTRODUCTION

Deposition of sediments discharged by streams into a reservoir often reduces storage capacity and is also responsible for water contamination mostly by suspended mineral and organic matter. Information regarding the rate of sedimentation is essential for defining appropriate measures for controlling sediment inflow and for managing the available storage in a particular reservoir. Suspended matter plays an important role in water quality management since it is related to water soil erosion process. Synoptic information on suspended matter is difficult to obtain only from in situ measurement. This can be solved by modeling water soil erosion effect using Digital Elevation Model, climate data, soil type parameters and land-use/land-cover data obtained from remote sensing multitemporal imageries.

When dealing with soil erosion modeling one can choose from several different tools ranging from indicator-based approaches to advanced process-based models. Assessment procedure proposed by Józefaciuk and Józefaciuk (1992) is widely adopted in Poland and can be provided as an example of the former. In this approach the potential water erosion hazard is estimated on the basis of soil texture, slope classes and the amount of annual precipitation. Actual erosion risk can also be assessed when land use, size and shape of plots and tillage system are taken into consideration (for details see e.g. Jadczyszyn et al. 2003). As a result, one can obtain spatial pattern of erosion risk, but only in qualitative manner – in form of erosion hazard classes. Approaches of this kind are designed for agricultural applications and are not useful for sediment yield prediction.

At basin scale (over 50 km^2 approx.) sediment yield can be estimated based on empirical relations with basin properties such as drainage area, rainfall or slopes. The Factorial Scoring Model (Verstraeten et al. 2003, de Vente et al. 2005) can be mentioned as example of such semi-quantitative tools.

Advanced physically-based erosion models such as WEPP (Laflen et al. 1991), EUROSEM (Morgan et al. 1998) or EROSION-3D (Schmidt et al. 1997) result in spatial pattern of erosion and deposition and enable estimation of the sediment loads to rivers or reservoirs (Schmidt and Werner 2000). However, applications of physically-based models in catchment scale are not always possible, because of their large data requirements.

Undoubtedly, the most known soil erosion modeling tools are the Universal Soil Loss Equation (USLE, Wischmeier and Smith 1978) and its revised version – RUSLE (Renard et al. 1997). These empirical models are still in use in many studies. The difficulty with their application for sediment delivery assessment arises from the fact that the USLE was originally developed for assessment of soil loss due to sheet and rill erosion in the scale of agricultural plot. It is possible to apply it with some modifications in the catchment scale, but the model is still not capable to predict sediment deposition within the catchment. The USLE approach has been adopted for sediment production component in models such as USPED (Mitasova et al. 1998) or Watem/SEDEM (Van Rompaey et al. 2001). Sediment transport capacity for every grid cell is considered in these models. This enables to predict areas where deposition of transported sediment occurs. Applications of the Watem/SEDEM model for the assessment of sediment delivery to rivers and reservoirs were presented in many studies (e. g. Van Rompaey et al. 2001, Van Rompaey et al. 2003, Van Rompaey et al. 2005).

Estimation of sediment yield is also possible based on the (R)USLE model together with sediment delivery ratio (SDR) (see e. g. Krasa et al. 2005, Bhattarai and Dutta 2007). Sediment delivery ratio is the ratio of sediment yield at the catchment outlet to total erosion in the watershed.

2. STUDY AREA

Dobczyce Reservoir, located in the southern part of Poland has been selected as a tested object (Fig. 1).

Figure 1. Location of Dobczyce Reservoir

This reservoir was constructed twenty years ago (in 1987) in the Raba River valley between the towns of Myslenice and Dobczyce. The Raba River is one of the right side tributaries of the Vistula River, which is the principal link of river systems in Poland. The main purpose of Dobczyce Reservoir project was to supply the city of Cracow, which is situated about 30 km north from this area, with potable water. This reservoir (about 10 kilometers long and approximately 1 kilometer in wide) is situated in the upper part of the Raba River valley. The total catchment area of Dobczyce Reservoir is about 768 km² while the immediate watershed is about 72 km² and is mostly under forest cover and partly agriculture cultivated area. The water spread at full reservoir level is about 125 million cubic meters. From geological point of view the reservoir and its surroundings are located within the Western Flysch Carpathians which was folded up during the Alpine orogenesis in Miocene and Oligocene and is formed mostly with alternate beds of sandstones, slates and conglomerates. Within the study area the flysch is covered with the Quaternary sediments which consist of loess and glacifluvial clays, sands and pebbles. The youngest deposits in the Raba River valley and its tributaries are alluvial ones. The soils formed on the flysch rocks are differentiated due to the relief of the terrain and the intensity of morphogenetic processes. A soil cover on the tested area is mostly loess loam type: gley soil (*Stagnic Luvisols*) and fallow soil (*Haplic Luvisols*) (Skiba et al. 1998). This kind of soils, due to its dusty-grained character, is very tractable for water erosion process and can give a significant volume of suspended matter in reservoir water.

The climate of Dobczyce Reservoir area may be characterized with mean annual temperature of 8.6 ° C and mean annual precipitation of about 762 mm.

Four catchments in the immediate watershed of Dobczyce Reservoir were used as study areas (Fig. 2).

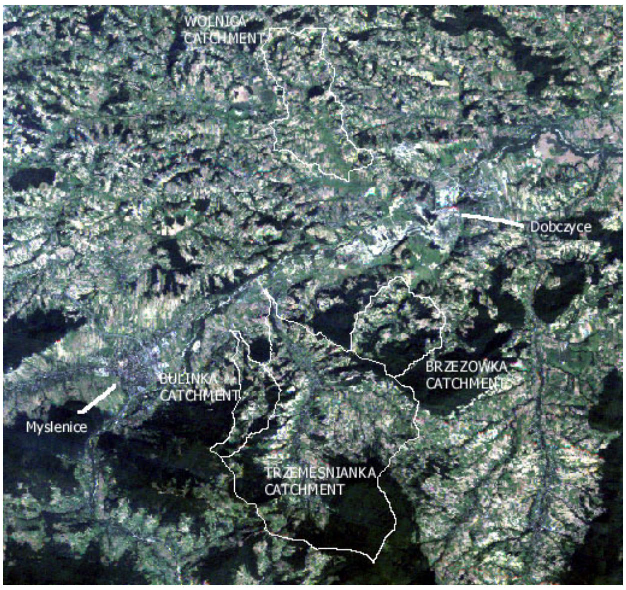

Figure 2. Modeled catchments with Landsat TM [123] color composite (year 1985) in the background

3. METHODOLOGY

3.1 Water soil erosion modeling

From many existing soil erosion modeling approaches which could be used as a tool for sediment delivery estimations, the RUSLE approach together with sediment delivery ratio estimation was chosen. Mean annual soil loss was calculated with the equation (1):

$$A=R\ K\ LS\ C\ P \tag{1}$$

where A = mean annual soil erosion rate (t ha^{-1} y^{-1})
R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1})
K = soil erodibility factor (t h MJ^{-1} mm^{-1})
LS = topographic factor (dimensionless)
C = crop management factor (dimensionless)
P = erosion control practice factor (dimensionless)

The RUSLE rainfall erosivity factor (R) was calculated using the Modified Fournier Index (Arnoldus 1977):

$$R = \sum_{i=1}^{12} p_i^2 / P \tag{2}$$

where R = rainfall erosivity factor
p_i = total amount of precipitation in *i*th month of the year
P = total amount of precipitation during the year.

Equations (3) and (4) (Renard et al. 1997) were applied to assess soil erodibility factor (K):

$$K = 0{,}0034 + 0{,}0405 \cdot \exp\left[-0{,}5\left(\frac{\log D_g + 1{,}659}{0{,}7101}\right)^2\right] \tag{3}$$

where K = soil erodibility factor (t h MJ^{-1} mm^{-1})
D_g = geometric mean weight diameter of the primary soil particles (mm)

D_g is a function of soil texture, calculated as:

$$D_g = \exp(0.01 \cdot \sum f_i \cdot \ln \frac{d_i + d_{i-1}}{2}) \qquad (4)$$

where d_i = maximum diameter for particle size class *i*
d_{i-1} = minimum diameter for particle size class *i*
f_i = the corresponding mass fraction

Values of C factor were assigned to land-use types based on published studies. A constant value of 1 was used for the erosion control practice factor (P).

The topographic factor (LS) was calculated with the use of USLE2D software (Desmet and Govers 1996b). In the algorithm applied (Desmet and Govers 1996a) a unit contributing area is used instead of upslope length. This adjusts the model to the two-dimensional topography.

Three different runoff routing algorithms are available in this software for drainage network modeling: the steepest descent algorithm (all runoff from the raster cell is routed to the single cell), flux decomposition algorithm (Desmet and Govers 1996b) (runoff can be routed to two cells) and multiple flow algorithm proposed by Quinn et al. (1991) (runoff can be divided between all lower cells in the neighborhood).

The slope-length component of the topographic factor is in USLE2D calculated according the equation (5) (Desmet and Govers 1996a):

$$L_{(i,j)} = \frac{(A_{(i,j)} + D^2)^{m+1} - A_{(i,j)}^{m+1}}{x^m \cdot D^{m+2} \cdot (22{,}13)^m} \qquad (5)$$

where L = slope-length
A = unit contributing area
D = grid spacing
x – correction factor
m – slope length exponent

User can choose various options for calculating the RUSLE LS factor: the equation originally developed for USLE by Wischmeier and Smith (1978), the equations of McCool et al. (1987, 1989), the equation proposed by Govers (1991) and the continuous function for slope steepness proposed by Nearing (1997).

McCool et al. (1987) proposed to calculate the slope steepness factor as:

$$\begin{aligned} S &= 10.8 \sin q + 0.03 && \text{for } s < 9\% \\ S &= 16.8 \sin q - 0.5 && \text{for } s \geq 9\% \end{aligned} \qquad (6)$$

where *q* = slope angle (degrees)
s = slope (percent)

The slope-length exponent *m* in this approach is calculated as (McCool et al. 1989):

$$m = \beta / (\beta+1) \qquad (7)$$

and for equal rill and inter-rill erosion

$$\beta = \frac{\sin q_{(i,j)} / 0{,}0896}{3 \cdot \sin^{0,8} q_{(i,j)} + 0{,}56} \qquad (8)$$

Value of β is multiplied by 0.5 if inter-rill erosion prevails and by 2.0 for prevailing rill erosion.

Govers (1991) proposed for rill erosion a value of 0.755 for the exponent *m* and the following equation for slope factor:

$$S = (\tan q / 0{,}09)^{1,45} \qquad (9)$$

According to Nearing (1997) slope steepness can be calculated as:

$$S = -1{,}5 + \frac{17}{(1 + e^{(2,3 - 6,1 \cdot \sin q)})} \qquad (10)$$

If this equation is chosen, the user has the possibility to use for values proposed by Wischmeier and Smith (1978) or McCool et al. (1989) for equal rill and inter-rill erosion.
In our study the upslope contributing area was calculated using all three available runoff routing algorithms. Then topographic factor was evaluated using algorithms based on equations of McCool et al. (1987, 1989), Govers (1991) and Nearing (1997) (with McCool slope length exponent). Nine maps of erosion rates were obtained.

3.2 Sediment delivery ratio

Empirical equations for SDR usually are based on variables such as catchment area, slope and land cover (Bhattarai and Dutta 2007). For example, Krasa et al. (2005) calculated the sediment delivery ratio values from watershed area, relief ratio and average runoff curve number value. They applied a lumped approach, but improved by division of the modeled catchment to smaller watersheds. Verstraeten (2006) points out that many authors use for the SDR estimations an exponential model and he generalizes it as:

$$SDR = \exp(-\lambda l) \qquad (11)$$

where SDR = sediment delivery ratio
l = travel distance
λ = a parameter proportional to particle size

Bhattarai and Dutta (2007) use similar relationship:

$$SDR = \exp(-\gamma t_i) \quad (12)$$

where t_i = travel time of overland flow from the *i*th overland grid to the nearest channel grid down the drainage path

They use fully distributed approach for estimation of SDR values and evaluate the travel time t_i from each cell by summing the travel time through each of the cells located in the flow path from the considered cell to the nearest channel cell. The travel time through a single cell is calculated as the flow length inside this cell divided by the velocity of flow. The overland flow velocity is considered to be a function of the slope and land use:

$$v = a\, S^{0.5} \quad (13)$$

where S = slope
a = a coefficient related to land use

Similar definition of travel time was used for SDR estimation by Ferro and Minacapilli (1995):

$$t = l/S^{0.5} \quad (14)$$

where t = travel time
l = flow length
S = slope

In our study equations (12) and (14) were used for sediment delivery ratio assessment. Values of SDR were calculated for each cell, but we resigned from summing the travel times along the flow paths. Instead, values of flow path length from considered cell to closest channel cell and the average slope in the watershed were used.

Finally, total amount of sediment load at the catchment outlet was obtained as a sum of simulated erosion rates (Eq. 1) multiplied by sediment delivery ratios (Eq. 12) calculated for all cells belonging to the catchment. It was assumed that sediment reaching the nearest stream channel is transported to the river outlet.

$$SY = \sum_{i=1}^{n} SDR \cdot A \quad (15)$$

where SY = sediment yield
n = total number of cells over the catchment
SDR = sediment delivery ratio for a cell
A = mean annual soil erosion rate for a cell

3.3 Model calibration

As soils covering modeled watersheds do not differ substantially we assumed that value of γ parameter in equation (12) will be the same for all watersheds. We tried to calibrate it on the basis of sediment loads measured for every watershed. A measure proposed by Nash and Sutcliffe (1970) was used to estimate the model efficiency

$$ME = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - P_{mean})^2} \quad \{16\}$$

where ME = model efficiency
n = number of observations
O_i = observed value
O_{mean} = mean observed value
P_i = predicted value

ME can be treated as a measure of the proportion of the initial variance accounted by the model (Verstraeten 2006). The closer its value approaches 1, the better the model predicts observed values. The model is inefficient if the calculated ME value is negative.

We used relative root mean square error (RRMSE) (Eq. 17) as another measure of the calibration accuracy. In addition, predicted total amount of sediment load at catchments outlets was compared with measured yield (Eq. 18).

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}}{\frac{1}{n}\sum_{i=1}^{n} O_i} \quad (17)$$

$$RE_{TSY} = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \quad (18)$$

where RE_{TSY} = relative error of total sediment yield from all modeled catchments

Model calibration was done for total sediment yield values (t year^{-1}). As reference data in calibration procedure (observed values) we used sediment loads at the outlets of four modeled watersheds. In years 1982-1984 (at the time when Dobczyce Reservoir was being constructed) detailed measurements of water quality (including concentrations of suspended sediment) were conducted together with detailed hydrological observations. Suspended sediment loads were calculated based on these data (Tab. 3).

4. DATA INPUT AND ASSESSMENT RESULTS

Soil erosion modeling was done based on raster data layers with 30-meter resolution. The evaluation of soil erodibility factor (K) was based on digital version of 1:25000-scale agricultural soil map. The map was rasterized from ArcView shape format. Values of D_g and K were estimated based on average sand (1.0-0.1 mm), silt (0.1-0.02 mm) and clay (< 0.2 mm) particles content in soil texture groups assigned to mapped soil polygons. Calculated soil erodibility values range from 0.0146 t h MJ^{-1} for sandy soils in small area in the lower part of Trzemesnianka catchment to 0.0397 and 0.0421 t h MJ^{-1} for soils originated on loess-like bedrock.

A land-use/land cover map was created by unsupervised classification of orthorectified Landsat TM images acquired in 1985. The ISOCLUST procedure available in IDRISI32 software was used for classification. It is an iterative self-organizing unsupervised classifier similar to the well-known ISODATA routine. User determines the number of clusters and the cluster seeding process is done with the CLUSTER module based on the color composite image chosen by the user. Then maximum likelihood classifier is used in the iterative process.

In our study, the ISOCLUST procedure was done twice – based on TM [457] and TM [154] color composite images. The obtained clusters were assigned to four land-use classes: agriculture, pasture/meadows, forest and built-up areas. The comparison of created maps showed the areas where the classification results were dubious (agriculture – pasture/meadows). The final classification of these clusters was based on the NDVI values.
Values of C factor were assigned to land-use types from land-use/land cover map as follows: 0.2 – for agricultural areas, 0.015 for pastures/meadows, 0.002 for forests and 0 (no erosion) for built-up areas.

Calculation of RUSLE topographic factor (LS) is based on a raster digital elevation model (DEM). DTED Level 2 DEM was used. This model is based on 1:50000-scale topographic maps. Nine maps of LS factor were obtained according to methodology described in section 3.1. Table 1 presents average values of LS for cells belonging to each modeled watershed.

Method	Wolnica	Trzemesnianka	Bulinka	Brzezowka
SD-M	2.85	8.15	7.02	6.09
SD-G	9.04	32.37	28.36	19.50
SD-N	3.88	10.43	9.18	7.60
FD-M	3.48	10.60	8.90	7.68
FD-G	12.97	47.20	40.57	28.03
FD-N	5.05	14.04	12.11	9.93
MF-M	3.33	10.09	8.42	7.27
MF-G	11.42	42.51	35.26	24.85
MF-N	4.72	13.28	11.26	9.29

Table 1. Average values of LS factor. Acronyms used for runoff routing algorithms: SD – steepest descent, FD – flux decomposition, MF – multiple flow. Abbreviations used for LS equations: M – McCool, G – Govers, N – Nearing.

Total amount of sediment reaching the catchments outlets was calculated using estimated annual rainfall erosivity values both for the year 1984 (as the closest to the acquisition date of Landsat image) and for the period of 1982-1984. The rainfall erosivity value was assumed to be a constant for the entire study area. Value of R obtained according to equation (2) based on monthly rainfall data measured in Dobczyce meteorological station were used. Rainfall erosivity for the year 1984 was estimated as 752 MJ mm ha^{-1} h^{-1} y^{-1} and average annual rainfall erosivity calculated for the period of 1982-1984 was 644 J mm ha^{-1} h^{-1} y^{-1}.

Equations (15), (1) and (12) were used to predict values of sediment yields at watershed outlets for the year 1984 and as average for the considered three-year period. In both cases the values were calculated using LS maps obtained with the use of different algorithms (see Table 1). Each time calculations were done with different values of γ (Eq. 12) and the model efficiency evaluated with equation (16).

Table 2 shows the best results (ME) of calibration done for the modeling of sediment yields in 1984. Sediment yields predicted for modeled watersheds using the approach with the highest ME value are presented in table 3.

Method	γ	ME	RRMSE	RE_{TSY}
SD-M	0.021	0.88	0.24	0.07
SD-G	0.046	0.59	0.44	0.24
SD-N	0.025	0.81	0.30	0.08
FD-M	0.024	0.84	0.28	0.16
FD-G	0.048	0.65	0.41	0.21
FD-N	0.030	0.78	0.32	0.13
MF-M	0.024	0.83	0.29	0.18
MF-G	0.047	0.65	0.41	0.23
MF-N	0.029	0.81	0.30	0.11

Table 2. Calibration results.

Calibration of the models based on average sediment yields for the years 1982-1984 failed. For all tested approaches negative values of ME were obtained.

Catchment	1982 observed	1983 observed	1984 observed	1984 predicted
Wolnica 8.7 km^2	60.2	19.0	4.6	3.1
Trzemesnianka 29.1 km^2	18.5	16.1	15.2	15.7
Bulinka 4.1 km^2	2.4	2.2	2.3	3.8
Brzezowka 5.3 km^2	6.2	6.0	6.3	3.8

Table 3. Sediment yield (t $year^{-1}$) measured and predicted for modeled watersheds.

5. CONCLUSIONS

The results obtained in our study show the existing potential of simple RUSLE/SDR-based modeling approach to predict the sediment delivery to Dobczyce Reservoir from its immediate watershed. Calibration results were influenced mainly by applied LS-equations. The influence of the runoff routing algorithms was weaker. The best result was obtained with the use of the steepest descent runoff routing algorithm and the LS-equations proposed by McCool et al. (1987, 1989) for prevailing interrill erosion. These equations gave the best results for other tested runoff routing algorithms as well. Worse results were obtained with equations assuming equal rates of rill and interrill erosion. The worst ones with LS-equation proposed by Govers (1991) for rill erosion. It leads to the conclusion that erosion in modeled watersheds was governed mainly by interrill processes.

The lack of success in calibration based on average sediment yield values from years 1982-1984 was due abnormal values measured for Wolnica catchment. Sediment yields measured in three other catchments show little year-to-year variance. In Wolnica catchment sediment yield in 1982 was thirteen times greater then in 1984. The differences in measured sediment yields occur mainly in winter months. This watershed differs from the remaining ones because it is located on the south slopes (at the north side of the existing reservoir). This can cause differences in climate conditions. It is possible that calculated rainfall erosivity factor was not appropriate for that watershed. Prevailing rill erosion may be another hypothesis explaining these differences.

Presented study should be treated as the beginning of research. We plan to test other models as well as validate them with sediment loads measurements done in 1990s and during last year. The research will also be expanded to evaluate the sediment delivery to the reservoir from its entire catchment.

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